Methods of information systems synthesis

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PARAMETRIC SYNTHESIS OF A ROBUST AUTOMATIC VEHICLE COURSE STABILITY SYSTEM

Abstract. Relevance of the research. One of the main safety features preventing accidents in modern vehicles is the automatic course stability system, which is activated during emergency braking under complex driving conditions. A wide range of external disturbances and rapid changes in the vehicle motion parameters during emergency braking require the course stability system to have properties of invariance to external disturbances and robustness to rapid changes in vehicle motion parameters. **The object of the research** is dynamic processes in a closed-loop automatic vehicle course stability system . **The subject of the research** is the selection of optimal values of the varied parameters of the electronic unit of the vehicle course stability system, which ensure high dynamic accuracy of the system and its robustness to rapid changes in the current vehicle speed. **Results**. An algorithm is proposed for selecting the optimal values of the variable parameters of the electronic control unit of the automatic vehicle course stability system with the simultaneous selection of the weight coefficients of the additive integral quadratic functional, which is a quantitative assessment of the system's accuracy and its robustness to rapid changes in vehicle speed during emergency braking.

Keywords: robust automatic system; emergency vehicle braking; sensitivity function; system with embedded models; additive integral quadratic functional.

Literature review and research problem statement

The central problem of the theory of automatic systems is the creation of automatic control systems that are capable of functioning effectively under conditions of uncertain values of the system's design parameters, as well as under conditions of a wide range of external disturbances acting on the control object.

During the operation of any technical system, its design parameters inevitably deviate, to varying degrees, from their nominal values, which leads to changes in the system's dynamic characteristics. Changes in the design parameters of an automatic system - whether in the controlled object or in the automatic controller - can be interpreted as internal disturbances of the automatic system. The property of the independence of the characteristics of an automatic system from changes in external disturbances is called the "invariance" of the system to their change, and the property of the independence of the characteristics of the system from changes in the values of its design parameters is called the "robustness" of the system. A technical system will be reffered to as robust in the following if a change in its design parameters does not lead to a significant change in its dynamic characteristics. The concept of the robustness of a technical system is closely related to the concept of the sensitivity of the system to changes in its design parameters, in other words, a system is robust if it is characterized by low sensitivity to changes in its design parameters.

In the 21st century, the global automotive industry has been characterized by the widespread use of course stability systems in vehicles of all classes - from executive class passenger cars to quarry dump trucks and fuel tankers with tank volumes of 20–22 m^3.

In [1], a mathematical model of a vehicle's disturbed motion during emergency braking is developed, which has the following form:

$$\dot{v}(t) = -\frac{2k_g}{M}p_0 - gf;$$
$$\ddot{\psi}(t) = -\frac{Bk_g}{2I}\Delta p(t) - \frac{2H_m M}{I} f v(t)\dot{\psi}(t);$$
$$I_k \Delta\ddot{p}(t) + f_k \Delta\dot{p}(t) + c_k \Delta p(t) = k_p k_{em} u(t);$$
$$\dot{y}(t) = -v(t)\psi(t), \tag{1}$$

and the solution to the problem of parametric synthesis of an electronic control unit that implements a control algorithm in the form:

$$u(t) = k_\psi \psi(t) + k_{\dot{\psi}}\dot{\psi}(t) + k_y y(t), \tag{2}$$

where $\psi(t)$ – is the angle of deviation of the longitudinal axis of inertia of the vehicle body from the given direction of movement;

$y(t)$ – is the lateral displacement of the center of mass of the vehicle from the given trajectory of movement;

$v(t)$ – is the current speed of the vehicle during emergency braking;

$\Delta p(t)$ – is the difference in brake fluid pressures in the brake lines of the right and left sides of the vehicle;

p_0 – is the brake fluid pressure at the outlet of the master brake cylinder;

k_g – is the brake cylinder gain;

k_{em} – is the gain of the electromagnet of the executive body;

k_p – is the gain of the hydraulic booster;

g – is the acceleration of gravity;

f – is the rolling resistance coefficient of the vehicle wheels;

M – is the vehicle mass;

I – is the moment of inertia of the vehicle relative to its own vertical axis;

H_m – is the distance from the surface of movement to the center of mass of the vehicle;

I_k – is the moment of inertia of the electromagnet rocker arm;

fk – is the coefficient of fluid friction in the rocker arm axis;

ck – stiffness coefficient of the locking spring;

$u(t)$ – output signal of the electronic control unit;

$k_\psi, k_{\dot\psi}, k_y$ – variable parameters, the values of which must be chosen from the condition of the minimum of the additive integral quadratic functional

$$I = \int_0^T \begin{bmatrix} \beta_1^2\psi^2(t) + \beta_2^2\dot\psi^2(t) + \\ +\beta_3^2 y^2(t) \end{bmatrix} dt, \qquad (3)$$

calculated on the solutions of the mathematical model of the disturbed motion of the closed-loop automatic vehicle course stability system, and the values of the weight coefficients β_1, β_2 and β_3 of the functional (3) are subject to deliberate selection.

In the 1950s, the first works on the development of the theory of invariant automatic systems appeared, the founder of which was B.M. Petrov and O.I. Kukhtenko. Later, the theory of invariant automatic systems was further developed in the works of V.M. Kuntsevich, B.M. Pshenichny and B.T. Polyak. In [2], the authors developed an invariant vehicle course stability system , in which the control algorithm is proposed in the form

$$u(t) = k_\psi\psi(t) + k_{\dot\psi}\dot\psi(t) + \\ +k_y y(t) + k_r \Delta p(t), \qquad (4)$$

or in the form

$$u(t) = k_\psi\psi(t) + k_{\dot\psi}\dot\psi(t) + k_y y(t) + \\ +k_r \Delta p(t) + k_{\dot r}\Delta\dot p(t). \qquad (5)$$

In [7] it was proved that in the case when the variable parameter kr of algorithm (4) is equal to

$$k_r = \frac{c_k}{k_p k_{em}}, \qquad (6)$$

then the degree of astaticism of the open-loop automatic vehicle stability system increases by one, which, in turn, inhances the invariance of the closed-loop system to the action of external disturbances, and if the varied parameters k_r and $k_{\dot r}$ algorithm (5) are equal to

$$k_r = \frac{c_k}{k_p k_{em}};\ k_{\dot r} = \frac{f_k}{k_p k_{em}}, \qquad (7)$$

then the degree of astaticism of the open-loop system increases by two units, further improving the system's invariance to external disturbances.

By the end of the 20th century, the theory of robust automatic systems received a significant impetus in its development in the works of B.T. Polyak, V.M. Kuntsevich, E.M. Potapenko, L.S. Zhitetsky, A.A. Tunik, V.B. Larin.

The mathematical model of disturbed motion of the closed-loop automatic vehicle course stability system (1), (2) is non-stationary. Indeed, the first equation of the system (1) is independent of the second, third and fourth equations and determines the vehicle's speed during emergency braking. In [14], to construct the stability regions of the non-stationary automatic vehicle course stability system, the authors used the method of "frozen coefficients", which lacks strict mathematical justification.

Therefore, the aim of the presented work is to design a robust automatic system, whose dynamic characteristics are largely independent of the current vehicle speed during emergency braking.

Main material

In [15], it was proposed to use sensitivity theory of automatic systems – specifically, sensitivity functions of an additive integral functional characterizing the dynamic accuracy of the automatic system with respect to a system parameter that changes during operation to solve the problem of parametric synthesis for robust automatic systems of moving objects.

For a closed-loop automatic vehicle course stability system described by (1), (2), this parameter is the instantaneous vehicle speed during emergency braking v(t).

Let's introduce a new variable

$$x(t) = \int_0^t \begin{bmatrix} \beta_1^2\psi^2(t) + \beta_2^2\dot\psi^2(t) + \\ +\beta_3^2 y^2(t) \end{bmatrix} dt, \qquad (8)$$

which satisfies the differential equation

$$\dot x(t) = \beta_1^2\psi^2(t) + \beta_2^2\dot\psi^2(t) + \beta_3^2 y^2(t) \qquad (9)$$

with initial condition

$$x(0) = 0. \qquad (10)$$

To the sixth-order mathematical model of the disturbed motion of the closed-loop vehicle course stability system (1), (2) with initial conditions:

$$\psi(0) = \psi_0; \\ \dot\psi(0) = \Delta p(0) = \Delta\dot p(0) = y(0) = 0 \qquad (11)$$

we add the differential equation (9) with the initial condition (10).

Integrating the system of differential equations (1), (2), (9) under the given initial conditions, we obtain

$$I = x(T). \qquad (12)$$

Let us consider the function

$$s(t) = \frac{\partial x(t)}{\partial v(t)}, \qquad (13)$$

which we will call the sensitivity function of functional (8) to changes in the current speed of the vehicle during emergency braking.

At any given moment in time $t \in [0, T]$. The sensitivity function (13) is calculated by the formula

$$s(t) = \frac{x^+[t, v(t) + \delta v] - x^-[t, v(t) - \delta v]}{2\delta v}, \qquad (14)$$

where the function $x^+[t, v(t) + \delta v]$ represents a solution to a system of differential equations

$$\dot v(t) = -\frac{2k_g}{M}p_0 - gf;$$

$$\ddot{\psi}^{+}(t) = -\frac{Bk_g}{2I}\Delta p^{+}(t) -$$
$$-\frac{2H_mM}{I}f[v(t)+\delta v]\dot{\psi}^{+}(t);$$
$$I_k\Delta\ddot{p}^{+}(t) + f_k\Delta\dot{p}^{+}(t) + c_k\Delta p^{+}(t) =$$
$$= k_pk_{em}\begin{bmatrix} k_\psi\psi^{+}(t) + k_{\dot{\psi}}\dot{\psi}^{+}(t) + \\ +k_yy^{+}(t) \end{bmatrix}; \qquad (15)$$
$$\dot{y}^{+}(t) = -[v(t)+\delta v]\psi^{+}(t);$$
$$\dot{x}^{+}[t, v(t)+\delta v] =$$
$$= \beta_1^2[\psi^{+}(t)]^2 + \beta_2^2\left[\dot{\psi}^{+}(t)\right]^2 + \beta_3^2[y^{+}(t)]^2$$

under initial conditions (10), (11).

Function $x^{-}[t, v(t)-\delta v]$ represents a solution to a system of differential equations

$$\dot{v}(t) = -\frac{2k_g}{M}p_0 - gf;$$
$$\ddot{\psi}^{-}(t) = -\frac{Bk_g}{M}\Delta p^{-}(t) -$$
$$-\frac{2H_mM}{I}f[v(t)-\delta v]\dot{\psi}^{-}(t);$$
$$I_k\Delta\ddot{p}^{-}(t) + f_k\Delta\dot{p}^{-}(t) + c_k\Delta p^{-}(t) =$$
$$= k_pk_{em}\begin{bmatrix} k_\psi\psi^{-}(t) + k_{\dot{\psi}}\dot{\psi}^{-}(t) + \\ +k_yy^{-}(t) \end{bmatrix}; \qquad (16)$$
$$\dot{y}^{-}(t) = -[v(t)-\delta v]\psi^{-}(t);$$
$$\dot{x}^{-}[t, v(t)-\delta v] =$$
$$= \beta_1^2[\psi^{-}(t)]^2 + \beta_2^2\left[\dot{\psi}^{-}(t)\right]^2 + \beta_3^2[y^{-}(t)]^2$$

In (14) and systems of differential equations (15) and (16), δv denotes the variation of the current vehicle speed.

Following [16], systems (15) and (16) are referred to as “embedded models”.

During the parametric synthesis of the robust vehicle course stability system, the main mathematical model of disturbed motion (1), (2) is integrated in parallel with the embedded models (15) and (16).

Based on the solutions of the embedded models, the sensitivity function (14) is continuously evaluated.

The integral quadratic performance functional of the main model (1), (2) is chosen as:

$$I = \int_0^T \begin{bmatrix} \beta_1^2\psi^2(t) + \beta_2^2\dot{\psi}^2(t) + \\ +\beta_3^2y^2(t) + \beta_4^2s^2(t) \end{bmatrix} dt, \qquad (17)$$

i.e. the basic model (1), (2) is supplemented by the equation

$$\dot{x}[t, v(t)] = \beta_1^2\psi^2(t) + \beta_2^2\dot{\psi}^2(t) +$$
$$+\beta_3^2y^2(t) + \beta_4^2s^2(t), \qquad (18)$$

where the sensitivity function s(t) is determined by the solutions of the embedded models and relation (14).

In the first stage of the process of parametric synthesis of a robust vehicle directional stability system, the values of the weight coefficients β_1, β_2, β_3 and β_4 of the additive functional (17) are estimated using the method described in [17].

In the second stage of the process, the value of the additive integral quadratic functional (17) is estimated by direct parallel integration of the main model (1), (2), (18) and the embedded models (14), (15), (16)

$$I = x(T, 0) \qquad (19)$$

at equal points of the set of permissible values of the varied parameters of the system $k_\psi, k_{\dot{\psi}}, k_y$, corresponding to the nodes of the Sobol grid.

In the third stage, the node of the Sobol grid is selected in which the functional (19) has the smallest value.

This node lies near the point of the global minimum of the functional (17).

At the fourth and final stage of the parametric synthesis process of a robust vehicle directional stability system, the point of the global minimum of the functional (17) is found using the Optimization Toolbox software of the MATLAB interactive environment or Minimize of the MathCAD interactive environment. The starting point for the optimization procedure is chosen as the previously identified Sobol grid node where functional (17) is minimal.

Let's conduct a comparative analysis of the optimal ESP system in terms of accuracy and the robust system during emergency braking of a car on asphalt concrete.

Fig. 1 shows transient processes in a closed ESP with additive functional (3).

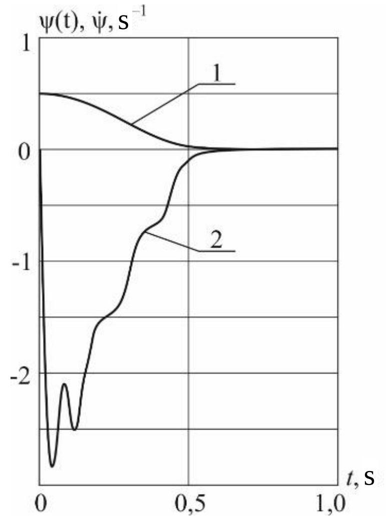
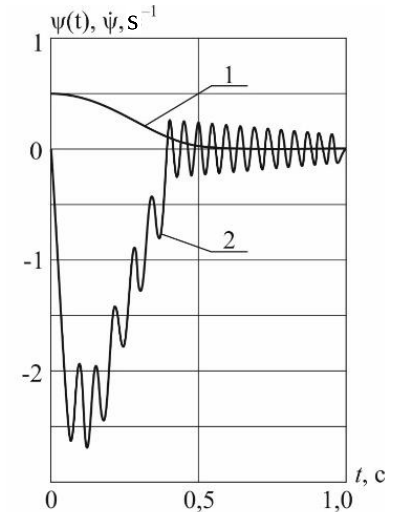


Fig. 1. Processes in an optimal EPS system: $1 - \psi(t); 2 - \dot{\psi}(t)$

The speed of such a system is 0.6 s, the maximum deviation of the angular velocity from zero does not exceed $\dot{\psi}_{max} = 2{,}8c^{-1}$, and the minimum value of the additive functional (3) is $I^{*} = 0{,}939$.

Fig. 2 shows processes in a robust system.

Analysis of Fig. 1 and 2 leads to the conclusion that increasing the level of robustness of the ESP system leads to a decrease in its accuracy, and the speed, on the contrary, increases. The decay time of transient processes decreases from 0.6 s to 0.45 s. It becomes clear that the requirements for accuracy and robustness contain an internal contradiction.



s

Fig. 2. Processes in a robust EPS system: $1 - \psi(t); 2 - \dot{\psi}(t)$

This contradiction is resolved by a compromise between the requirements for accuracy and robustness when minimizing the additive functional (17), the minimum value of which is $I^* = 1{,}159$

Conclusions and recommendations

The automatic vehicle course stability system comes into operation in the event of emergency braking in difficult road conditions or even complete off-road conditions, when a wide range of external disturbances act on the vehicle body.

In addition, the mathematical model of the disturbed motion of the closed-loop system of directional stability is non-stationary, due to the fact that it contains such a motion parameter as the current vehicle speed, which continuously and intensively changes during emergency braking. Therefore, modern automatic vehicle course stability systems must be, firstly, invariant to the action of external disturbances acting on the vehicle body, and, secondly, robust to changes in the operational values of the design parameters of the control object and the automatic controller, as well as to changes in the vehicle movement parameters.

The proposed article addresses the problem of parametric synthesis of an automatic vehicle course stability system that is optimal in terms of accuracy, taking into account the requirement of robustness to changes in the current vehicle speed during emergency braking. To solve the problem, elements of the sensitivity theory of automatic control systems, the theory of control systems with embedded models, and the theory of optimization of multi-criteria systems are involved. It is recommended to use the Sobol grid method, which implements numerical Monte Carlo methods for finding the global minimum of the integral optimality criterion. Some decrease in stabilization accuracy observed in the robust system is compensated by a noticeable increase in the speed of the robust system.

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Параметричний синтез робастної автоматичної системи курсової стійкості автомобіля

Є. Є. Александров, Т. Є. Александрова, Я. Ю. Моргун

Анотація. Актуальність дослідження. Одним із основних запобіжників аварійності сучасних автомобілів являється автоматична система курсової стійкості, яка вступає в дію при терміновому гальмуванні в складних умовах руху. Широкий спектр зовнішніх збурень і швидка зміна параметрів руху автомобіля в умовах термінового гальмування обумовлюють придання системі курсової стійкості властивостей інваріантності до дій зовнішніх збурень і робастності до швидкої зміни параметрів руху автомобіля. **Об'єктом досліджень** являються динамічні процеси в замкненій автоматичній системі курсової стійкості автомобіля. **Предметом досліджень** являється вибір оптимальних значень варійованих параметрів електронного блоку системи курсової стійкості автомобіля, які забезпечують високу динамічну точність системи і її робастність до швидкої зміни поточної швидкості руху автомобіля. **Результати.** Пропонується алгоритм вибору оптимальних значень варійованих параметрів електронного блоку керування автоматичної системи курсової стійкості автомобіля з одночасним вибором вагових коефіцієнтів адитивного інтегрального квадратичного функціоналу, який являється кількісною оцінкою точності системи і її робастності до швидкої зміни швидкості руху автомобіля в процесі термінового гальмування.

Ключові слова: робастна автоматична система; термінове гальмування автомобіля; функція чутливості; система з вбудованими моделями; адитивний інтегральний квадратичний функціонал.